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ERRORS IN THE 48-HOUR DEPTH OF CYCLONES PREDICTED BY THE P. E. MODEL AS RELATED TO THE MAGNITUDE AND LOCATION OF LATENT HEAT RELEASE WITHIN THE STORM SYSTEMS

by

A. James Wagner

Suitland, Md.

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A. James Wagner
Extended Forecast Division

ABSTRACT

The 48-hour surface pressure progs made from the 1200 GMT runs of the Primitive Equation Model operational at NMC between October 1968 and May 1969 were examined for errors which might be related to failure to properly handle the effects of latent heat release.

Although this study did not yield a "correction formula" which could be operationally used to improve the P.E. forecasts, two interesting diagnostic results were obtained: (1) The greatest errors in underprediction of the central pressure of cyclones occurred in cases when most of the precipitation was in areas where the mean 1000-500 mb. thickness was colder than normal, while the depth of storms where most of the precipitation was in areas of abnormally warm mean thickness was also somewhat underpredicted. Storms in which the precipitation was about equally distributed between warm and cold thicknesses were on the average forecast a little too deep. (2) The range between the most underpredicted and most overpredicted cyclones (in other words the uncertainty of the predictions) increased as the magnitude of the thickness anomaly gradient in the vicinity of the storm increased, although the sign of the error did not appear to have any clear relationship with the thickness anomaly gradient or other parameters.

INTRODUCTION AND THEORETICAL BACKGROUND

Although the six-layer Primitive Equation Model in operational use at the National Meteorological Center since 1966 now contains the effects of latent heat release and other non-adiabatic terms (Shuman and Hovermale, 1968), it frequently fails to predict sufficient deepening of cyclones east of the central United States. Many of the most rapidly deepening systems were noted to be associated with intense frontal zones (as shown by a strong gradient of thickness or thickness departure from normal) and relatively heavy (other than convective) rainfall, often located primarily in the sector of the storm where the thickness is substantially above normal.

It has long been realized that the addition of thermal energy to the atmosphere by sensible heating from below, particularly over the oceans in winter, and by the latent heat released during the precipitation process, can have profound effects on both the large-scale circulation (Clapp, 1961) and on individual storm systems (Petterssen, Bradbury, and Pedersen, 1962). Depending upon whether the heat is added in regions of relatively high or relatively low temperature, the eddy potential energy available for subsequent conversion to kinetic energy may either increase or decrease for an individual cyclone or a mean standing wave in the atmospheric circulation.

There has been some uncertainty as to whether the effects of sensible and latent heat release are energy-producing or energy-consuming on the scale of standing eddies in the general circulation. Clapp (1961) found that the answer depended on the method of calculation used, and felt that the preferable technique (heat-balance method) showed that non-adiabatic heating added available potential energy to the atmosphere at mid-latitudes in winter.

In a study of non-adiabatic heating related both to individual situations and the average circulation for the month of January 1959, Wiin-Nielsen and Brown (1962) found that while zonal available potential energy was created, eddy available potential energy was destroyed by the non-adiabatic processes, at least for the larger scales of motion. There was evidence from their study, however, that in some instances eddy available potential energy was created on the scale of wave numbers 7 and 8, which correspond to the short-wave cyclonic disturbances.

Petterssen, Bradbury, and Pedersen (1962) found that the inclusion of non-adiabatic effects greatly improved the thickness tendency "fore-casts" of individual cyclonic systems over the North Atlantic Ocean, and that the addition of sensible and latent heat from the ocean contributed to cyclone development.

Palmén (1959) showed that in certain extreme situations the selective release of large amounts of latent heat from heavy precipitation in abnormally warm tropical air masses contributed significantly to the generation of eddy available potential energy and the rapid deepening of cyclones in the eastern U.S. One of the cases he examined involved the severe extratropical cyclone which developed from Hurricane Hazel. It can easily be understood how the absorbtion of a tropical storm into the warm sector of a highly baroclinic extratropical system could lead to rapid deepening due to a large latent heat contribution.

Danard has made extensive case studies of deepening cyclones over central North America (1964, 1966a, 1966b, 1966c) and found that the inclusion of latent heat release in precipitation areas led to increased vertical motion in the precipitation field with associated high-level divergence and low-level convergence, and a net production of kinetic energy. Short-range forecasts of the storms out to 36 hours were considerably improved by inclusion of latent heat (using a quasi-geostrophic model). Donaldson (1967) found similar indications of improvement in the operational 36-hr. cyclone forecasts by the NMC Primitive Equation Model when the effects of latent heat were added to the model.

Taking a quite thorough approach to the problem, Johnson (1967) and Dutton and Johnson (1967) showed that when the problem is rigorously formulated in isentropic co-ordinates and viewed three-dimensionally, the addition of sensible heat at high pressure (in the lower atmosphere) and subtraction of heat by radiation to space at low pressure (above the highest cloud layer in the upper troposphere) produces a net increase of available potential energy in a given storm system even though the air mass which is being heated the strongest is on the cold side of the storm. The three-dimensional isentropic view point had always been neglected in earlier diagnostic numerical investigations, perhaps leading to some of the paradoxical conclusions that sensible and latent heat release may have had a weakening rather than strengthening effect on atmospheric perturbations.

The importance of the vertical distribution of non-adiabatic heating effects suggests that careful attention should be paid to properly incorporating these processes in multi-level models. Until July 1969, the NMC operational six-layer P.E. model had effectively only a one-layer specification of latent heat, since it was assumed to have the same vertical apportionment everywhere (Shuman and Hovermale, 1966). Beginning in July 1969, the latent heat and precipitation could be released in either or both of the two lower tropospheric layers, excluding the surface boundary layer (Technical Procedures Bulletin No. 26, June 30, 1969).

RESULTS AND DISCUSSION

In order to get an idea whether the operational NMC six-layer P.E. model was properly handling the effects of latent heat, and hopefully to discover any relatively simple empirical correction rule which might be applicable, all suitable storms which developed over the eastern two-thirds of the United States during the months from October 1968 through May 1969 were examined. A storm was considered "suitable" if it had already formed a closed center east of the Continental Divide at the initial time, was still over or close enough to land 48 hours later so that at least the major portion of the observed 0 to 24 and 24 to 48 hour precipitation distributions were measured over land stations, and the storm had unambiguous continuity and a closed center at both 24 and 48 hours.

In this study, only the errors in the 48-hr. central pressure of cyclones as predicted by the P.E. model were considered. A previous report by Donaldson (1967) dealt with both the displacement and development errors of the 36-hr. P.E. model forecasts of Highs and Lows. Another study by Wagner (1967) related the displacement errors only of the P.E. model forecasts for 48 through 120 hours to the regions through which the Highs and Lows moved. Both studies showed that on the average the largest and most consistent errors in the predicted depth and displacement of Lows were off the Atlantic Coast of the North American continent, an area of large sensible and latent heat input to the atmosphere in winter.

The parameters measured which were considered potentially relevant to the current study were:

Observed central pressure at 0, 24 and 48 hours.

Observed 1000-500 mb thickness anomaly gradient (both direction and magnitude) measured near estimated storm positions at 12 and 36 hours.

24-hr. precipitation fields observed from 0 to 24 and 24 to 48 hours, and their correlation with the corresponding thickness anomaly fields.

The 48-hr. central pressure of the cyclone as predicted by the P.E. model.

Most of these measurements had to be approximate.

The P.E. model output did not always print the central pressure and it had to be extrapolated in some instances, a technique which Donaldson (1967) pointed out often led to estimating the central pressure too high.

The total area and amount of precipitation and its correlation with the thickness anomaly field could not be measured with a planimeter due to time limitations, hence they were estimated subjectively by five semi-quantitative categories according to their predominant characteristics.

Predominant Max. Amount	Category
< .25	1
.25 to .50	2
.50 to 1.00	3
1.00 to 2.00	4
> 2.00	5

Area	Category
Spotty	1
Small	2
Medium	3
Large	4
Very Extensive	5

Position of Precip. Area Relative to Sign of Thickness Anomaly	Category
All or nearly all in negative anomaly	-2
Largely in negative anomaly	-1
About equal	0

A scatter diagram was plotted relating the 48 hour prog error to an approximate measure of the estimated contribution of latent heat release to generate eddy available potential energy (and hence presumably to increased eddy kinetic energy as manifested by deepening of the surface storm system). A rough estimate of the total latent heat contribution throughout the entire 48-hr. period was obtained by adding the multiple products of the amount, area and correlation categories estimated at 12 and 36 hrs, the middle of the two 24-hr. subperiods. The larger the multiple product in a positive (negative) sense was, the greater was the probable eddy potential energy generation (destruction). The results of this were essentially negative, as the points appeared to have an almost completely random scatter and no trend line was even subjectively suggested by the appearance of the distribution.

The 48-hr. predicted central pressure change was also plotted against the 48-hr. error, in the anticipation that perhaps the development of the most rapidly deepening storms would be underestimated the most. Again, however, the scatter was essentially random and no useful conclusion could be drawn.

The errors in the 48 hr. P.E. progs were also plotted against the sum of the observed thickness anomaly gradients at 12 and 36 hr. (fig. 1), in the expectation that perhaps the strength of the thickness field relative to normal (a measure of the anomalous available potential energy) might affect the deepening of systems. Although this relationship had nothing explicitly to do with precipitation, the main purpose of this study, an interesting result was discovered at this point. The algebraic value of the 48 hour P.E. prog error did not have a clear relationship to the sum of the thickness anomalies, but its magnitude did. In other words, the stronger the thickness anomaly gradient, the greater the uncertainty of the accuracy of the 48-hr. P.E. prog.

Physically, this result suggests that the P.E. model as currently run may not have enough resolution to accurately incorporate the complex interactions which occur in strong frontal zones. This has long been suspected, but higher resolution must await the advent of computers at least an order of magnitude faster than the CDC 6600 currently in use.

The relationship between the 48 hr. P.E. prog error and the thickness anomaly field was also demonstrated in another way. The differences between the greatest positive (or least negative) and the greatest negative (or least positive) algebraic 48-hr. P.E. prog errors were linearly correlated with the sums of the 12- and 36-hr. observed thickness anomaly values which had at least two associated P.E. prog error measurements. Since the thickness anomaly gradients were estimated only to the nearest 100 feet per degree of latitude, most values of the thickness parameter had two or more related error points.

The derived linear regression equation took the form

$$\delta P = 6.7 + 0.78\ \Delta H$$

where δP is the range of uncertainty in the 48 hr. P.E. predicted central surface pressure value (in mb), and ΔH is the sum of the observed 12 and 36 hr. 1000-500 mb thickness anomaly gradients (in hundreds of feet per degree latitude).

It should be noted that in practice only the predicted Q.P.F. distributions and 12 and 36 hr. thickness anomaly fields would be available, but the P.E. model does have a tendency to make compensating errors at the 1000-mb and 500-mb levels. There is however, a characteristic error of predicting too much frontogenesis in the vicinity of a storm, which might compensate some for the fact that statistically derived relationships are usually conservative.

This equation says that over the range of thickness anomaly sums observed in this study, the average uncertainty of a 48 hr. P.E. surface prog for a similar sample at a similar time of year would vary from about 7 mb for very weak thickness anomaly fields to about 20 mb for the strongest observed fields in this sample.

The correlation coefficient between the uncertainty of the 48 hr. P.E. progs and the thickness anomaly sums was 0.51, indicating that about one-fourth the variance of the total uncertainty in the 48-hr. forecasts could be related to the magnitude of the thickness anomaly gradients in the vicinity of the storm centers.

A similar linear regression equation was derived relating the <u>average</u> magnitude of the 48-hr. P.E. error to the sum of the thickness anomaly gradients at 12 and 36 hours. This equation took the form

$$\overline{E} = 2.4 + 0.44\ \Delta H$$

where $\overline{E}$ is the average magnitude of the error in 48-hr. central pressure of cyclones as predicted by the P.E. model. The equation specifies that the average magnitude error would range from about 2-1/2 mb for a storm in a weak thickness anomaly field to about 8-1/2 mb for the strongest observed field in this sample.

The correlation coefficient is only 0.32 in this equation, which means that only about 11 per cent of the variance of the average magnitude of the 48-hr. P.E. cyclone surface central pressure predictions could be related to the magnitude of the thickness anomaly gradients near the storm centers.

The direction of the thickness anomaly gradient did not appear to be related to either the actual deepening or the error in the predicted deepening of storms in any consistent way.

Although the values of latent heat release for the generation of eddy available potential energy as estimated by the triple product of the numbers categorizing the amount, total area, and position of the precipitation relative to the sign of the thickness anomaly did not have any apparent linear relationship with the errors in the 48-hr. P.E. forecasts, it was found that the largest errors did occur within certain ranges of the triple product parameter. In general, the P.E. model failed to deepen enough those storms which presumably had large latent heat contributions to eddy available potential energy; and paradoxically, the model had even greater errors of underdevelopment for storms in which the latent heat release was apparently destroying eddy available potential energy. There were mostly small errors, both positive and negative, for storms in which the latent heat did not appreciably either augment or diminish the eddy available potential energy.

These results are shown in Tables 1 and 2 below, where the mean algebraic error in mb of the 48-hr. P.E. surface storm centers is shown ranked for different categories of estimated latent heat release. Table 2 is simply a combination of the results in Table 1 into larger categories. Due to the relatively small number of cases, it is difficult to determine whether these results are statistically significant.

TABLE 1--Mean algebraic error of 48-hr. P.E. cyclone central pressure ranked for different categories of estimated eddy available potential energy generation.

Category	>45	31 to 45	16 to 30	1 to 16	-15 to 0	-30 to -16	-31 to -45
No. of Cases	10	11	12	7	5	7	3
Mean Algebraic Error (mb)	+4.1	+3.9	-0.5	+1.1	-4.0	+4.6	+15.3

TABLE 2--Results of Table 1 combined into fewer and larger categories.

Category	>31	30 to -15	<-15
No. of Cases	21	24	10
Mean Algebraic Error (mb)	+4.0	-0.8	+7.8

The mean positive error (representing 48-hr. central pressures predicted too high) for storms in which the latent heat release was positively correlated with the thickness is not surprising, and suggests the P.E. model fails to fully incorporate the energy-producing effects of strongly positively correlated latent heat and temperature fields. This may be due to insufficient horizontal or vertical resolution in the model. Actually, during the period from which the data for this study were obtained, the vertical distribution of latent heat release was assumed constantly apportioned between the two lowest free troposopheric layers, with 75% in the lower of the two layers (Shuman and Hovermale, 1968, and Technical Procedures Bulletin No. 26, 1969). Currently the proportion occurring in each layer can be controlled internally by the model itself, although greater vertical resolution may be desireable and obtainable at a later date.

The characteristic behavior of the model to overdeepen Lows in situations where there was little or no correlation between the thickness and latent heat release fields may mean that the model has a slight bias toward overdevelopment in general, perhaps related to its tendency to overly strengthen frontal zones which was mentioned earlier.

The largest errors of failing to deepen the P.E. 48-hr. forecast cyclone central pressure enough occurred when the thickness and latent heat fields were negatively correlated. At first glance this might appear paradoxical, since the latent heat would be presumably reducing the eddy available potential energy if it were primarily released in the cold air. However, when the problem is viewed isentropically, as Dutton and Johnson (1967) believe it should, a reasonable physical explanation is possible.

Most of the cases of negatively correlated thickness and latent heat release occurred during February 1969, a period of "low index" circulation when cold air masses penetrated to low latitudes and were extensive over the United States. It is possible that considerable sensible heating from below (at high pressure) may have occurred, particularly in those storms near the East Coast, which were some of the strongest deepeners. Dutton and Johnson (1967) showed that this process can also increase the available potential energy of a storm system, particularly when coupled with radiational cooling from the top of the cloud deck at high levels (low pressure) in the upper troposphere. It is believed that this was at least a contributing factor in most of the storms which were characterized by extensive colder than normal air masses and which were usually not predicted deep enough by the P.E. model. Although precipitation primarily in cold air is a characteristic of the later occluded stages of a cyclone and thus an effect of deepening rather than a cause, a problem in horizontal or particularly vertical resolution of the model is suggested as a possible reason for the error. Recent changes in the model suggest there may be an improvement in this area (Technical Procedures Bulletin No. 31, 1969).

It was previously noted that the magnitude of the 48-hr. P.E. prog errors, or the uncertainty in the prediction, was related to the thickness anomaly gradient. It was felt that the 48 - hr. P. E. prog errors might be jointly related (probably not linearly) with the thickness anomaly gradient and the number characterizing the probable latent heat release contribution to the generation of eddy available potential energy. The values of the 48-hr. prog errors were plotted on a graph with these two parameters as co-ordinate axes, and the results are shown in Figure 2. It can be seen that most of the negative errors (storms predicted too deep) occurred with moderate thickness anomaly gradients and small correlations of latent heat release and thickness anomaly. The greatest positive errors (storms not predicted deep enough) occurred with strong thickness anomaly gradients and either large positive or large negative correlations of latent heat release and thickness. A tendency for positive errors of predicted deepening to occur with weak thickness anomaly gradients and large positive correlations of latent heat release with thickness appeared puzzling at first. However, it was noted that many of the points in that part of the graph were for storms which had considerable convective activity. A "C" follows the number giving the error of these predictions. The storms which had considerable squall line activity were mostly in the spring when thickness gradients are weaker, and most of the activity is usually in the warm part of the storm. Consequently, more available potential energy may have been generated in these cases.

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